Supersymmetry at HERA

Chi Nhan Nguyen
DESY / ZEUS
Hamburg – Germany

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- RPV at HERA
- Squark Production in RPV SUSY
  - General Search
  - Bosonic Stop Decays
  - Stop Production
- Superlight Gravitinos in RPV SUSY
- Summary and Outlook

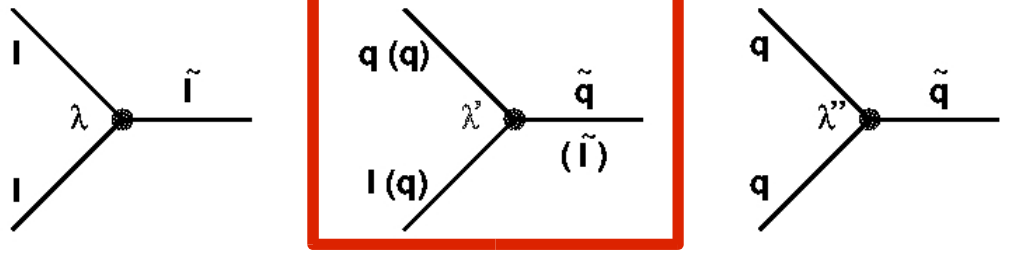
R-Parity at HERA

- **RPV SUSY:** $\Rightarrow$ Resonant Squark Production via s-channel with masses up to $\sqrt{s}$

- $R_p=(-1)^{3B+L+2S}$ multiplicative, discrete Symmetry:
  - +1 (SM Particles)
  - -1 (SUSY Particles)

  - Additional Terms in Superpotential:

$$W_{\not R_p} = \underbrace{\lambda_{ijk} L_i L_j \bar{e}_k}_{\not L} + \underbrace{\lambda'_{ijk} L_i Q_j \bar{d}_k}_{\not L} + \underbrace{\lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k}_{\not B} \ldots$$



  - allows Single Production of SUSY particles
  - allows Decay of LSP (Lightest Supersymmetric Particle) to SM Particles

- **HERA: Leading Order Diagrams proceed through 2. term**
  $\Rightarrow$ Resonant Production of SUSY Particles possible via λ'_{ijk}

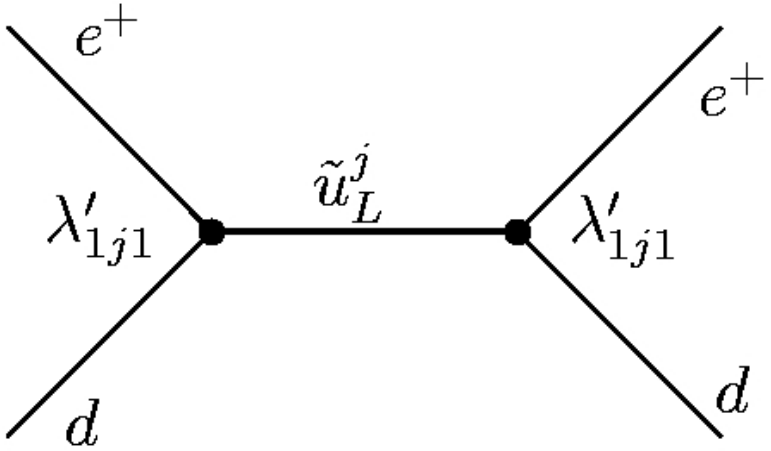
Search for Squark Production in RPV SUSY

- Squark Masses up to $\sqrt{s}$
- Narrow Width Approximation:

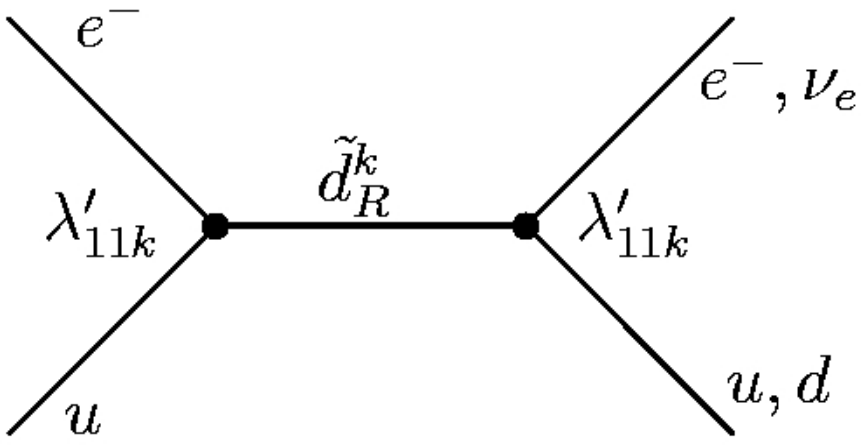
$$\sigma(e^+p \to \tilde{u}_L^j) \sim \lambda'^2_{1jk} \cdot d^k(x = \frac{M^2_{\tilde{q}}}{s})$$
$$\sigma(e^-p \to \tilde{d}_R^k) \sim \lambda'^2_{1jk} \cdot u^j(x = \frac{M^2_{\tilde{q}}}{s})$$

- Electrons and Positrons probe different squarks and couplings
- Direct RPV decays (like scalar Leptoquark):

$e^+d \longrightarrow \tilde{u}_L, \tilde{c}_L, \tilde{t}_L$



$e^-u \longrightarrow \tilde{d}_R, \tilde{s}_R, \tilde{b}_R$



High E_T e + jet (Backg: NC DIS)

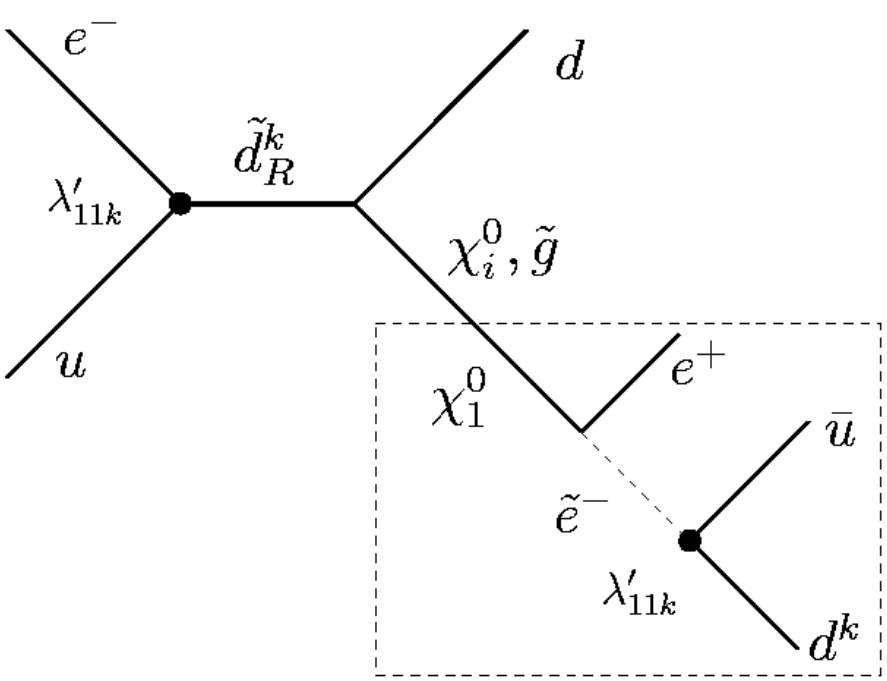
High E_T ν + jet (Backg: CC DIS)

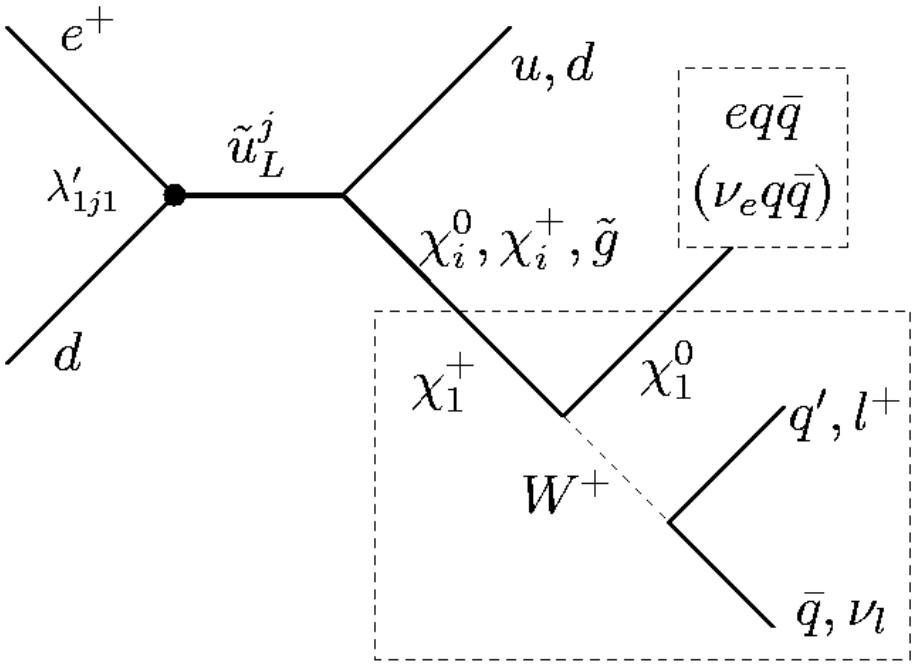
Gauge Decays

- **Gauge Decay of squarks:** $\tilde{q} \to \tilde{\chi}_i^0 q$ $\tilde{q} \to \tilde{\chi}_i^{\pm} q'$ $\tilde{q} \to \tilde{g} q$

Subsequent Gaugino Decay via cascade: Large variety of final states

- e+/- + multiple jets (Backg: NC DIS)
- e-/+ „wrong sign“ + multiple jets (Backg: bg-free!“)
- ν + multiple jets (Backg: CC DIS)
- e (ν) + l + multiple jets (Backg: small contrib. from NC, CC)





- **In this Search: Almost full coverage of BR's (depend on parameters)**

Squark Production: lq-channel

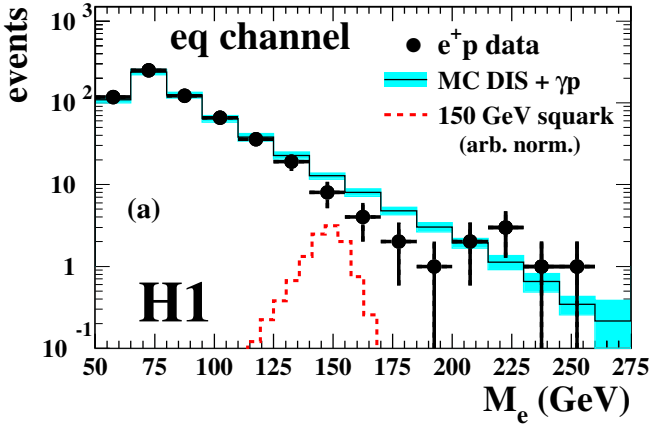
- **H1, Data:** 64.3 pb^{-1} e^+p , 13.5 pb^{-1} e^-p

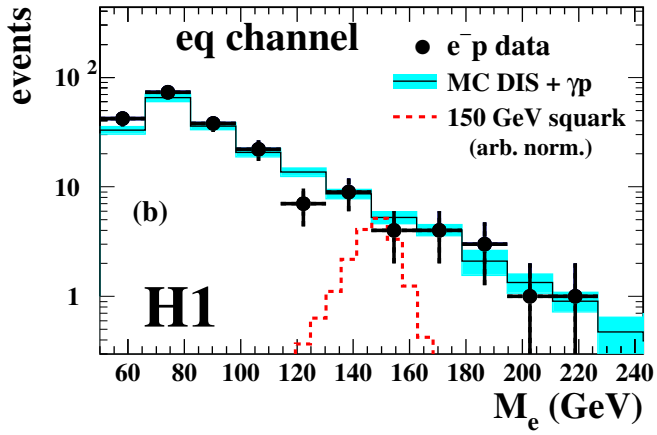
- **Selection**
  - Exclusive Selection for each channel
  - High Q^2
  - **eq-channel:**
    - $P_{T,e} > 16$ GeV, isolated
  - **νq-channel:**
    - $P_{T,miss} > 30$ GeV
    - No Lepton $p_T > 5$ GeV found

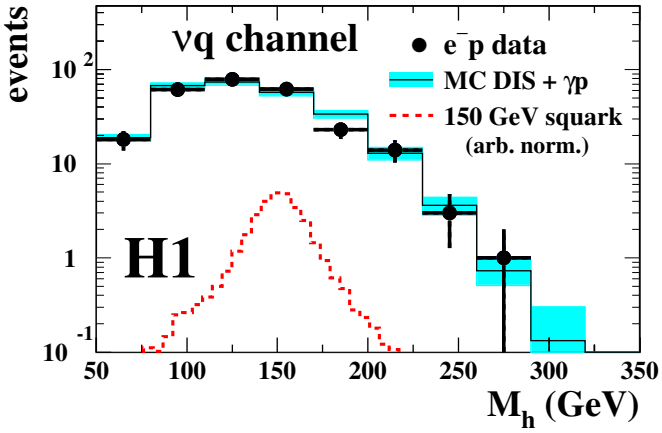
- Resonance in M_{inv} (M_h) at Squark Mass expected for Signal - Resolution 3-6 (15) GeV
- Typical Efficiencies: 30-60%

- No „wrong sign electron“ found

No deviaton from SM expectation







Search for Squark Production: Summary

Channel	e^+p collisions Data	e^+p collisions SM expectation	e^-p collisions Data	e^-p collisions SM expectation	Efficiency
eq	632	628 ± 46	204	192 ± 14	$30-50\,\%$
νq	—	—	261	269 ± 21	$40-60\,\%$
eMJ ("right" charge)	72	67.5 ± 9.5	20	17.9 ± 2.4	$15-50\,\%$
eMJ ("wrong" charge)	0	0.20 ± 0.14	0	0.06 ± 0.02	$10-30\,\%$
$eeMJ$	0	0.91 ± 0.51	0	0.13 ± 0.03	$15-45\,\%$
$e\mu MJ$	0	0.91 ± 0.38	0	0.20 ± 0.04	$15-35\,\%$
νeMJ	0	0.74 ± 0.26	0	0.21 ± 0.07	$15-40\,\%$
νMJ	30	24.3 ± 3.6	12	10.1 ± 1.4	$10-60\,\%$
$\nu\mu MJ$	0	0.61 ± 0.12	0	0.16 ± 0.03	$15-50\,\%$

- **Measurements in all Channels are compatible with SM**

  $\Rightarrow$ **Calculation of Exclusion Limits**

Squark Production: Constraints on MSSM

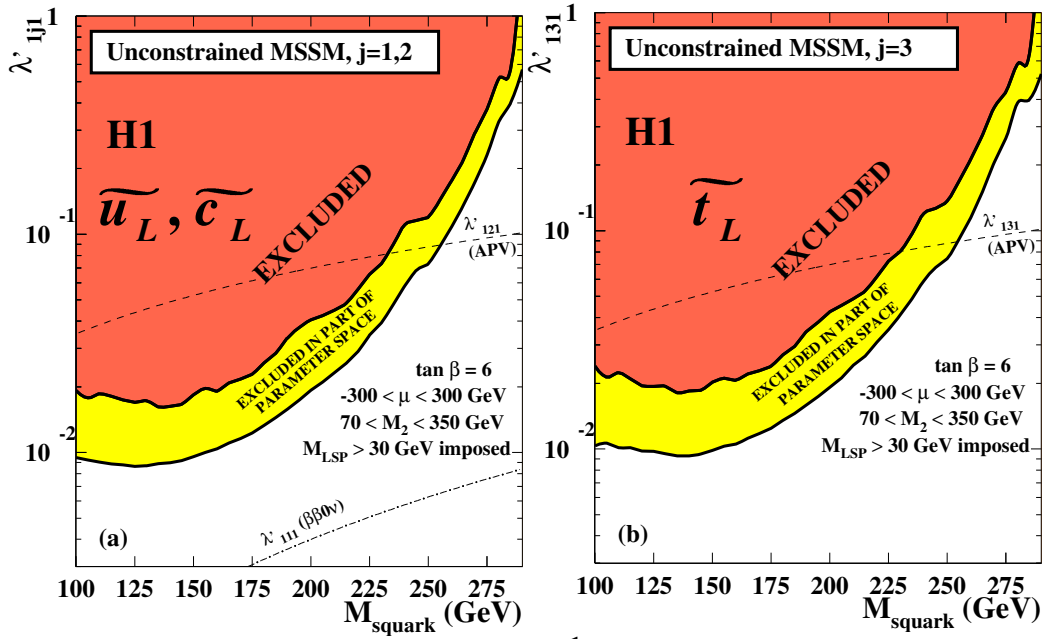
- **MSSM Parameter Scan:**
  - $\tan\beta = 6$
  - $70\ \text{GeV} < M_2 < 350\ \text{GeV}$
  - $-300\ \text{GeV} < \mu < 300\ \text{GeV}$
  - $M_{\tilde{l}} = 90\ GeV$

- **Limits almost independent of SUSY Parameters**

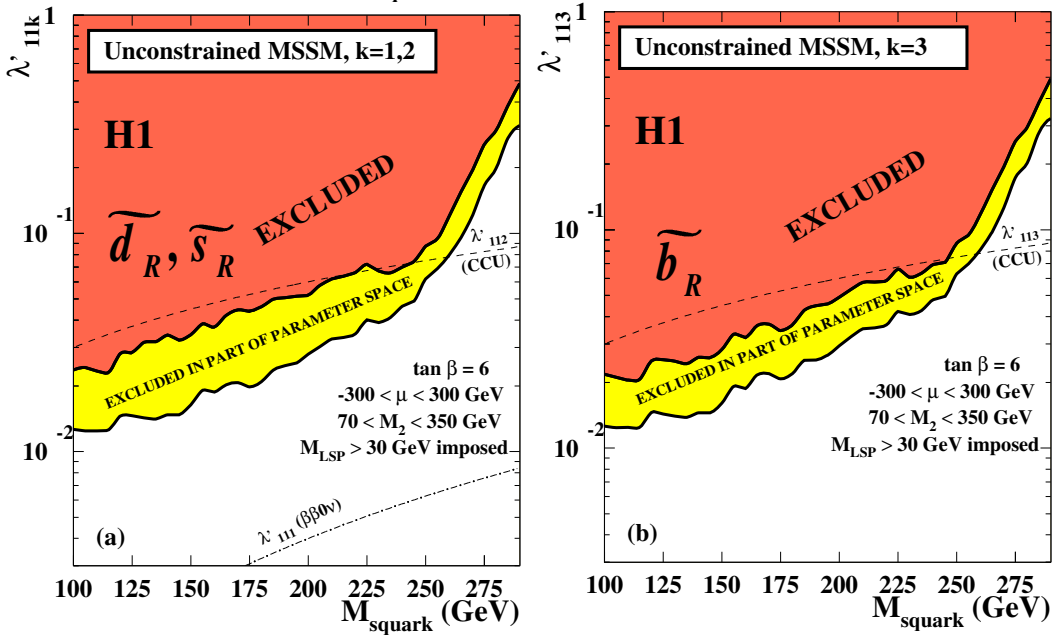
- **Strongest bounds on λ' for 2. and 3. family squarks**

- $\lambda'_{1j1} = 0.3\ (\lambda'_{11k} = 0.3) \sim \sqrt{4\pi\alpha_{em}}$:
  $M_{\tilde{q}} < 275\ GeV\ (280\ GeV)$

e+p:



e-p:

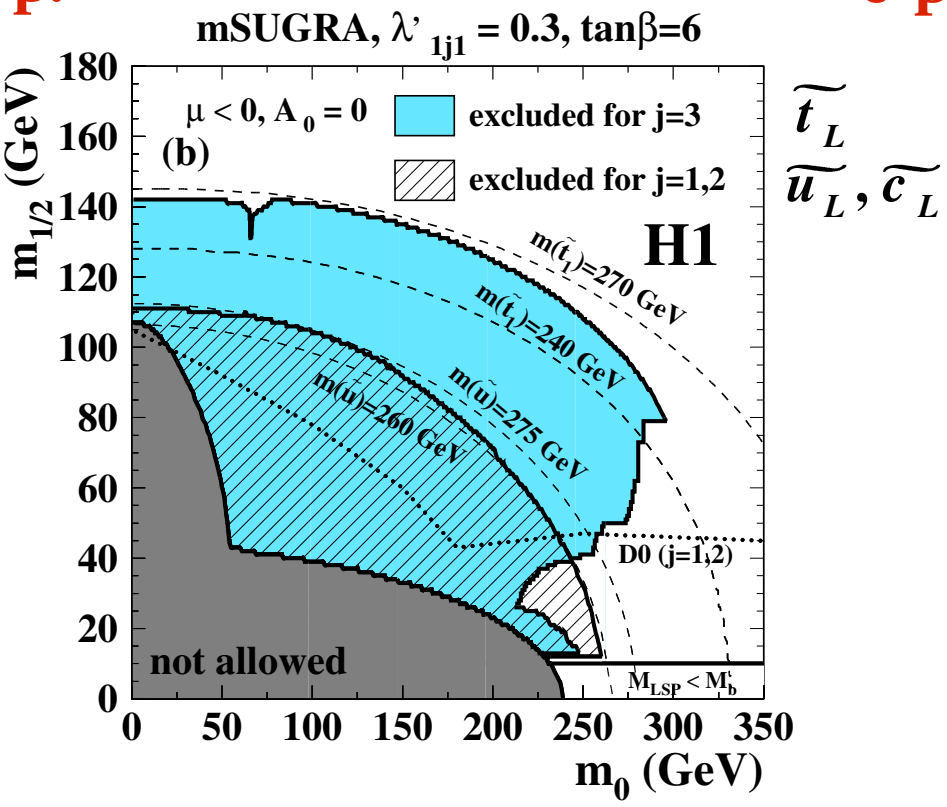


Squark Production: Constraints on mSUGRA

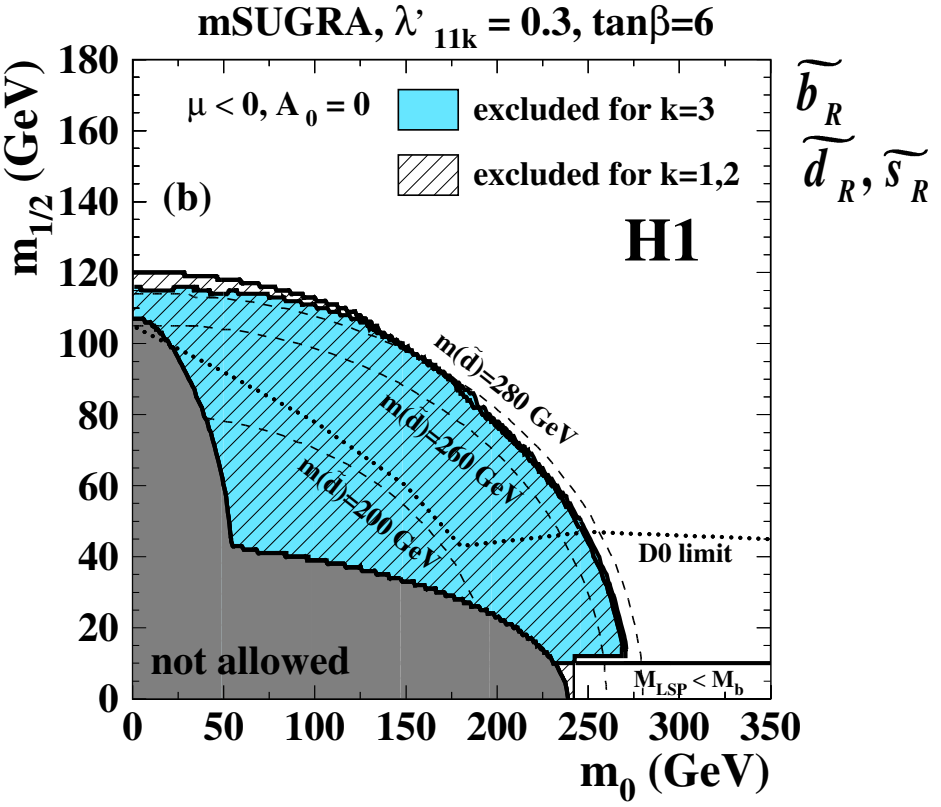
- **mSUGRA Parameters:**
  - $\tan\beta = 6$
  - $\mathrm{sign}(\mu) = -1$
  - $A_0 = 0$
  - $\lambda'_{1j1} = 0.3$ $(\lambda'_{11k} = 0.3)$ $\sim \sqrt{4\pi\alpha_{em}}$

- Limits follow squark isomass curves
- Medium $\tan\beta$: HERA more sensitive then Tevatron
- $M_{\tilde{q}}$ up to ~280 GeV excluded

e+p:



e-p:



Bosonic Stop Decays in RPV SUSY

- **Large Mixing in 3. generation possible:**

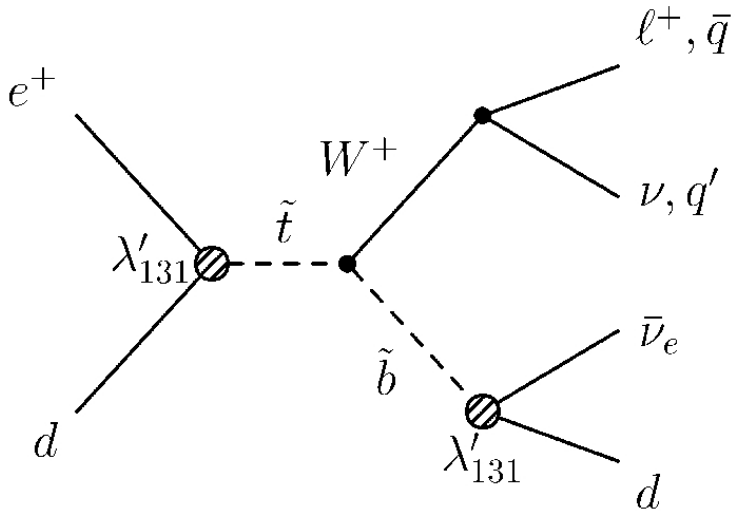
$\tilde{b}$ or $\tilde{t}$ can be rather light through large mixing:

$$\begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{f}} & \sin\theta_{\tilde{f}} \\ -\sin\theta_{\tilde{f}} & \cos\theta_{\tilde{f}} \end{pmatrix} \begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix}$$

$$m^2_{\tilde{t}_1} = \tfrac{1}{2}(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} - \sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4m_t^2 a_t^2}) \qquad a_t^2 = A_t - \mu\cot\beta$$

Motivation: Excess of isolated high pt lepton events at H1 (Talk by A. Schoening) can be explained by bosonic stop decays
(T. Kon et al., Mod. Phys. Lett. A12 (1997) 3143)

Signature: 3 jets + $p_{T,miss}$ or jet + lepton + $p_{T,miss}$



Assumptions (choice of MSSM Parameters):

$M_{\tilde{b}} < M_{\tilde{t}}$

$\tilde{t} \to \tilde{q}\chi$: kinematically forbidden

$M_{\tilde{t}} > M_{\tilde{b}} + M_W$

otherwise $\tilde{t} \to ed$ dominant

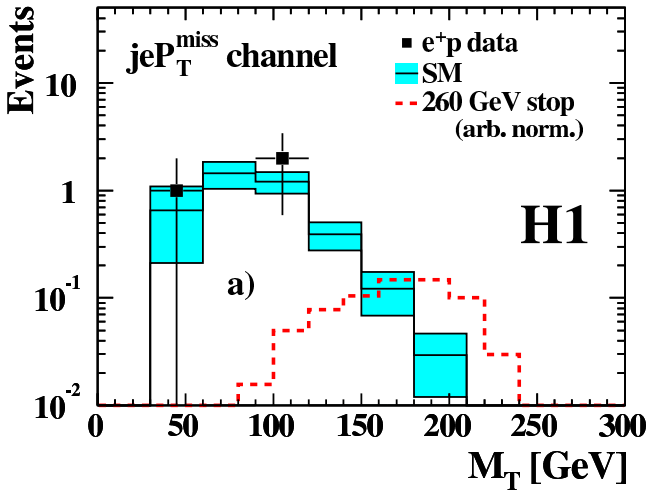
H1, Data 1994-2000 e+p: 67.9 pb^{-1} ($\sqrt{s}$ = 319 GeV), 37.9 pb^{-1} ($\sqrt{s}$ = 301 GeV)

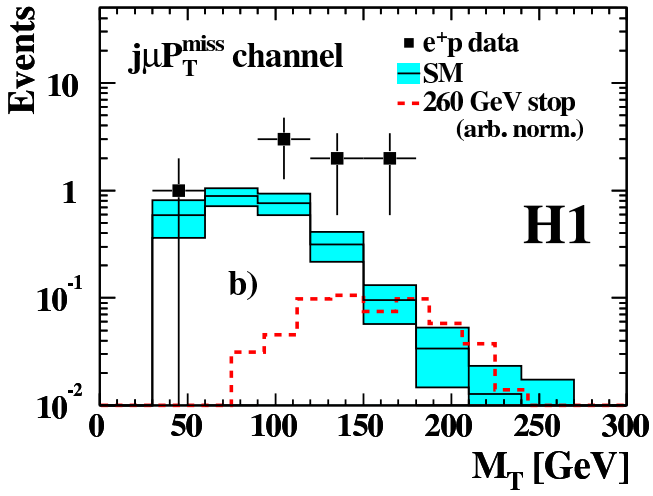
Bosonic Stop Decays: Mass Spectra

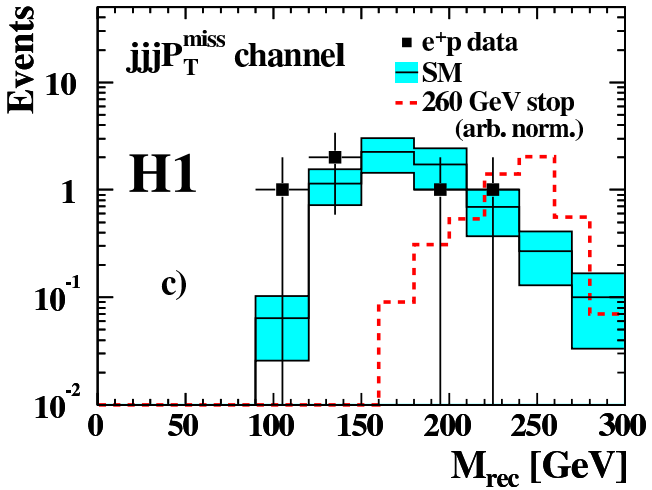
- **Selection $jlP_{T,miss}$-($jjjP_{T,miss}$)-channel:**
  - $P_{T,e(\mu)} > 10$ GeV
  - $P_{T,jet} > 10$ GeV (20, 15 ,10 GeV)
  - $P_{T,miss} > 12$ GeV (25 GeV)
  - Angular Cuts

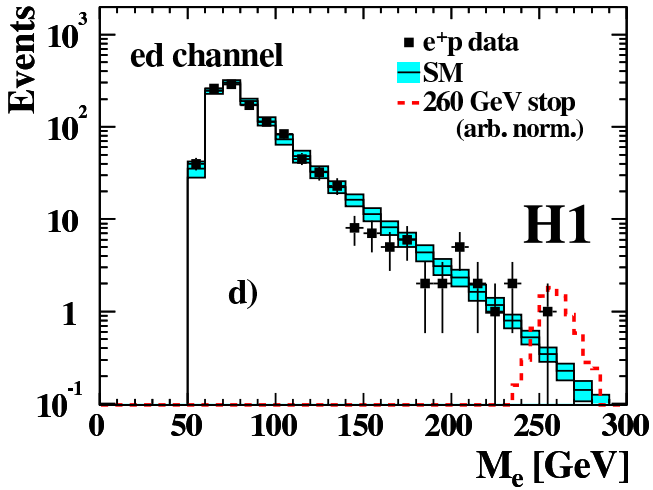
- **Typical Efficiencies: 30-50%**

- **Slight excess in $j\mu P_{T,miss}$ channel**







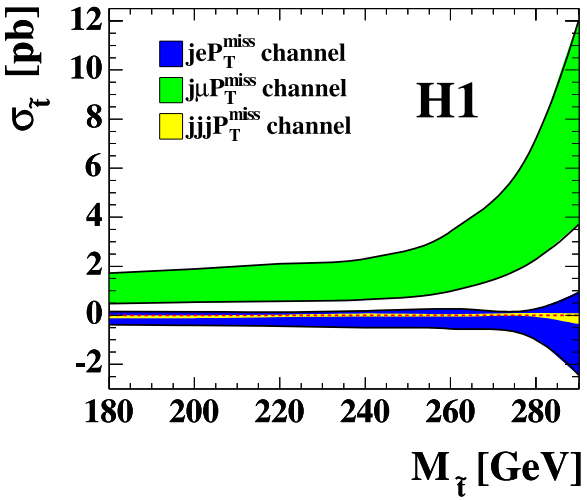


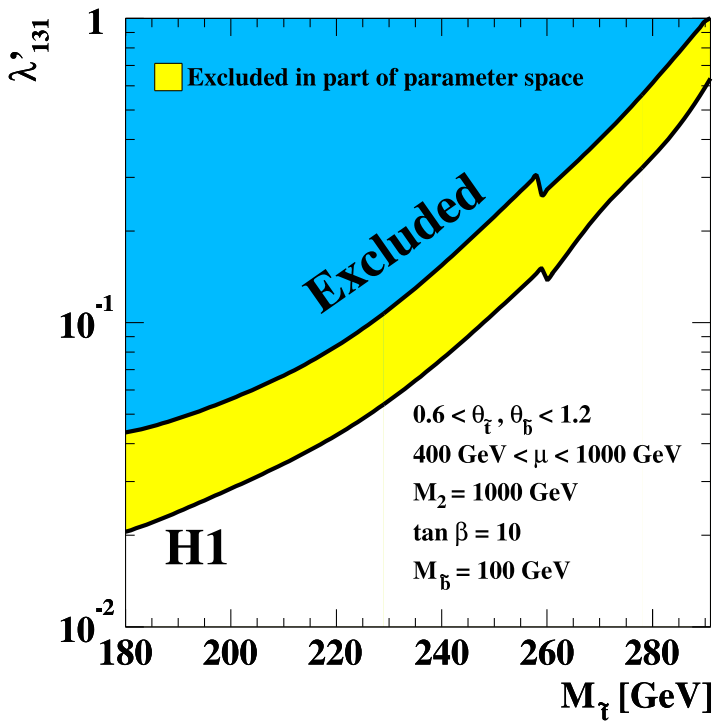
Bosonic Stop Decays: Limits

- Bands: allowed cross section regions
- Probability for fluctuation of $jjjP_{T,miss}$ rates towards rates compatible with $j\mu P_{T,miss}$ cross section is ~1%

⇒ **Isolated high P_T leptons cannot be interpreted as bosonic stop decays!**

→ Constraining MSSM parameters





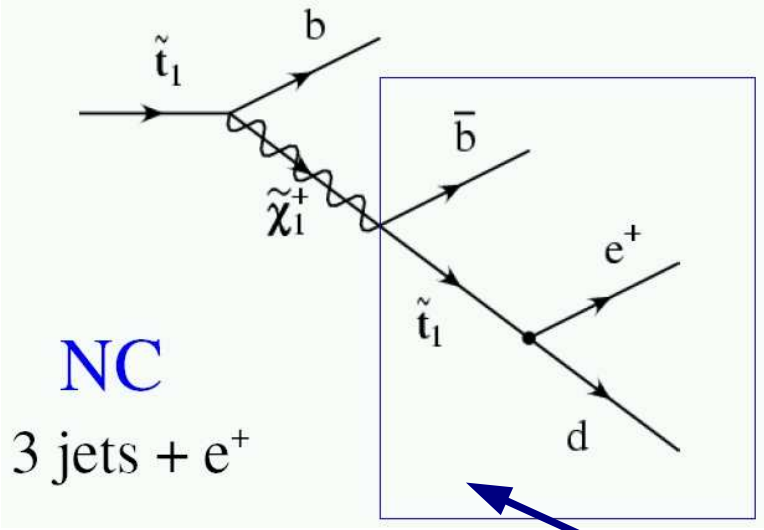
- **MSSM Parameter Scan:**
  - tan β = 10
  - M_2 = 1000 GeV
  - 400 < μ < 1000 GeV
  - $0.6 < \theta_{\tilde{t},\tilde{b}} < 1.2$

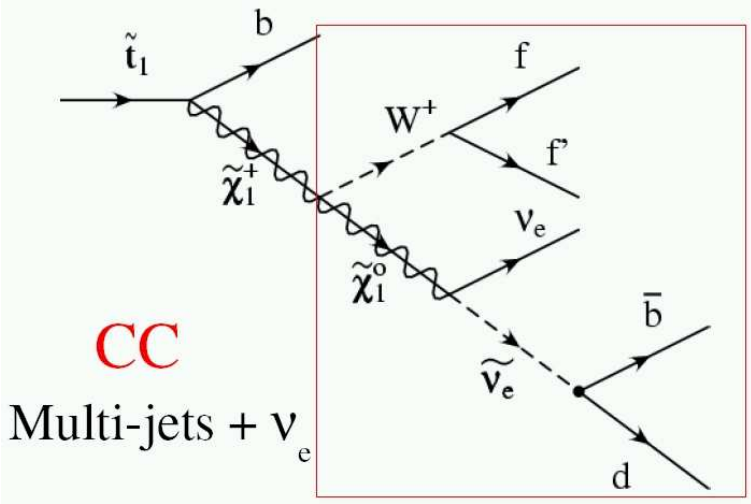
⇒ Stop masses up to ~275 GeV excluded for $\lambda'_{131} = 0.3$

- **Similar Results for** tan β = 10 and M_2 = 400 GeV

Stop Production in RPV SUSY

- **Gauge decays of stop:**





- **Assumptions:**
  - $40\ \text{GeV} < M_{\chi^0} < 100\ \text{GeV}$
  - $M_{\chi^0} < M_{\chi^+} < M_{\tilde{t}} < M_{\tilde{b}}$
  - $M_{\tilde{t}} - M_{\chi^+} = \Delta M \geq 10\ \text{GeV}$
  - Mass of all other sfermions ~1 TeV
  - λ'_{131} dominant

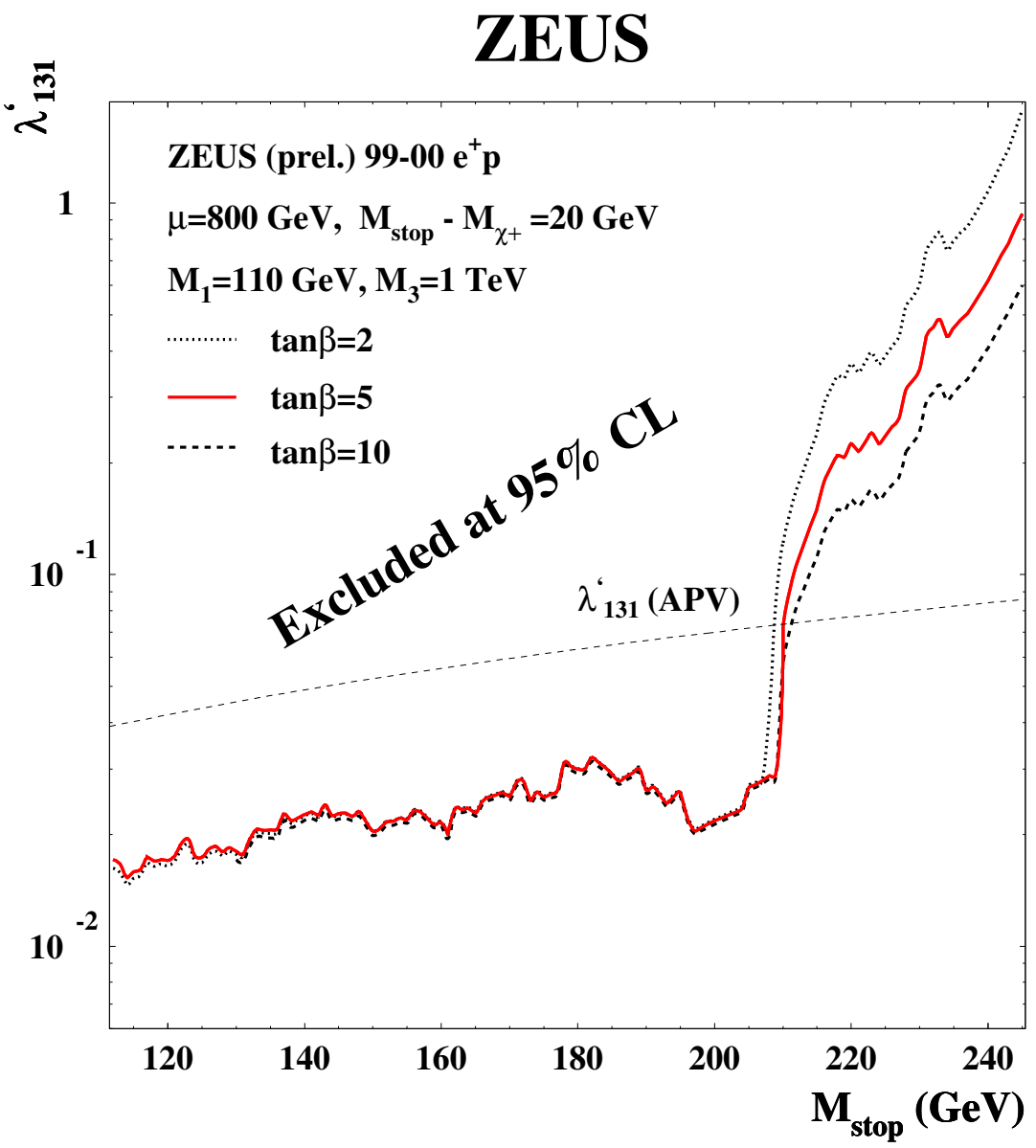
Right now: Only NC channel analysed

Stop Production: Prelimnary Results

- **MSSM Parameter Scan:**
  - tan = 2, 5, 10
  - M_1 = 110 GeV
  - M_3 = 1 TeV
  - $|\mu|$ = 600,800,1000 GeV
  - $\Delta M_{\tilde{t}\chi^+} = 10, 20, 30$ GeV

- **Results for each parameter point very similar for stop masses below ~200 GeV**

- **Limits on λ'_{131} improved for stop masses below ~210 GeV**



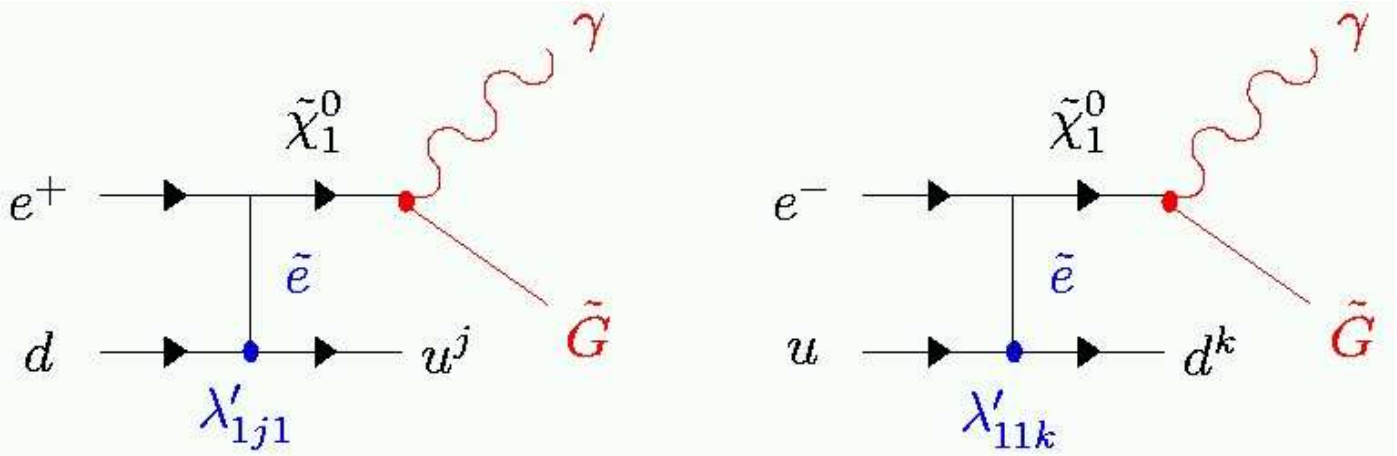
Superlight Gravitinos

- **GMSB**
  - Gravitino is LSP (< 1 GeV), NLSP: Neutralino, short lifetime
  - 6 new Parameters:
    - sign μ, tan β Λ: Overall mass scale for SUSY Particles
    - F_0: SUSY Breaking Scale, M(Gravitino) = $F_0/(\sqrt{3}\, M_P)$
    - M: Mass of messenger particle N: Number of messenger particles

- **Neutralino production via t-channel selectron exchange**

  $\Rightarrow$ Independent of squark masses (strong constrains by Tevatron)

  $\Rightarrow$ Depend on selectron and neutralino masses (lower constrains by LEP)



- **Signature:**
  - Isolated photon, jet and $P_{T,miss}$

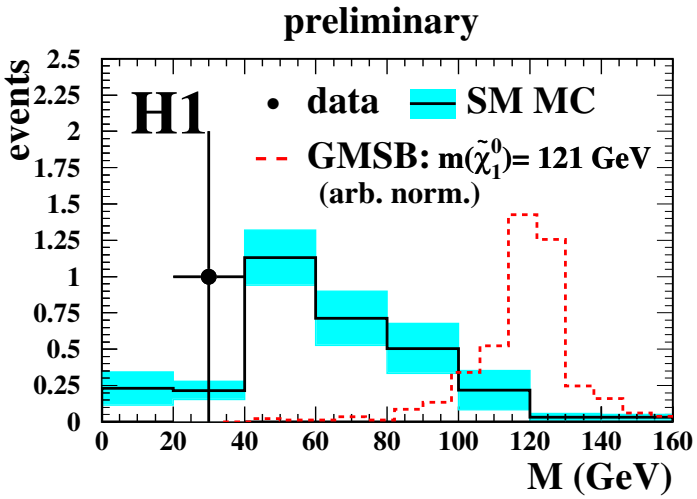
Gravitinos: Event Selection

- **H1, Data:** 64.3 pb^{-1} e$^+$p, 13.5 pb^{-1} e$^-$p

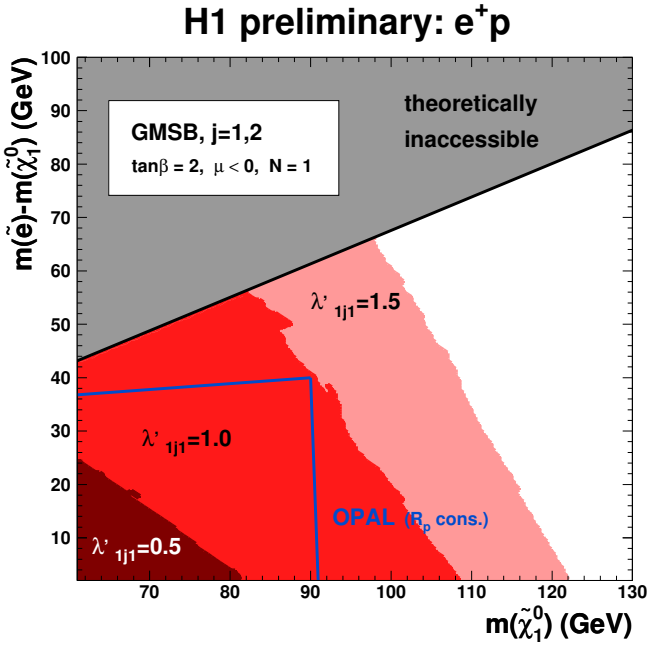
- **Selection**
  - $P_{T,miss} > 25$ GeV
  - $P_{T,jet} > 5$ GeV
  - $P_{T,\gamma} > 15$ GeV, isolated
  - Angular cuts

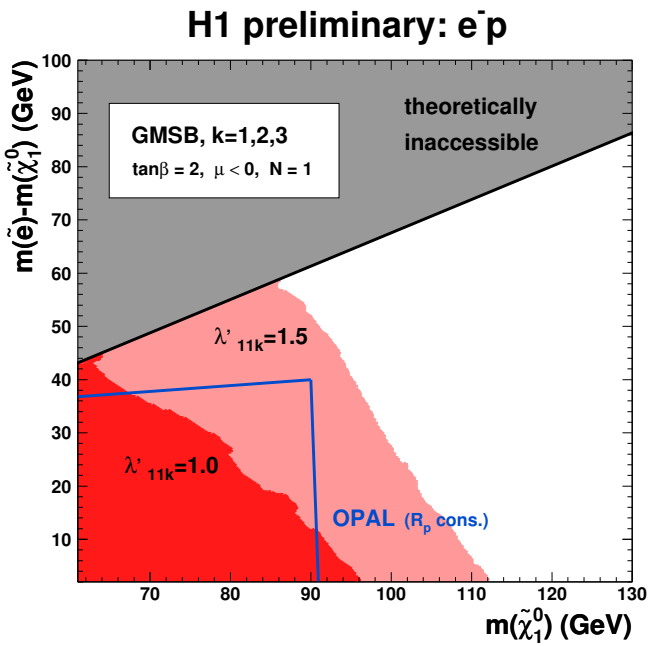
- **GMSB Parameters:**
  - $\tan\beta = 2$, sign(μ) = -1
  - N = 1, $\lambda' = 0.5, 1.0, 1.5$
  - Λ and M transformed to $m_{\tilde{e}_L} = \left(m_{\tilde{e}_R} = m_{\tilde{e}} \right)$, $m_{\chi_1^0}$,

- $\lambda' = 1.0$: $m_{\chi_1^0} > 108$ GeV and $m_e > 138$ GeV (First time at HERA: independent of squark mass)



- **Only one candidate after final cuts**
  ⇒ **Deriving limits on parameters in GMSB**

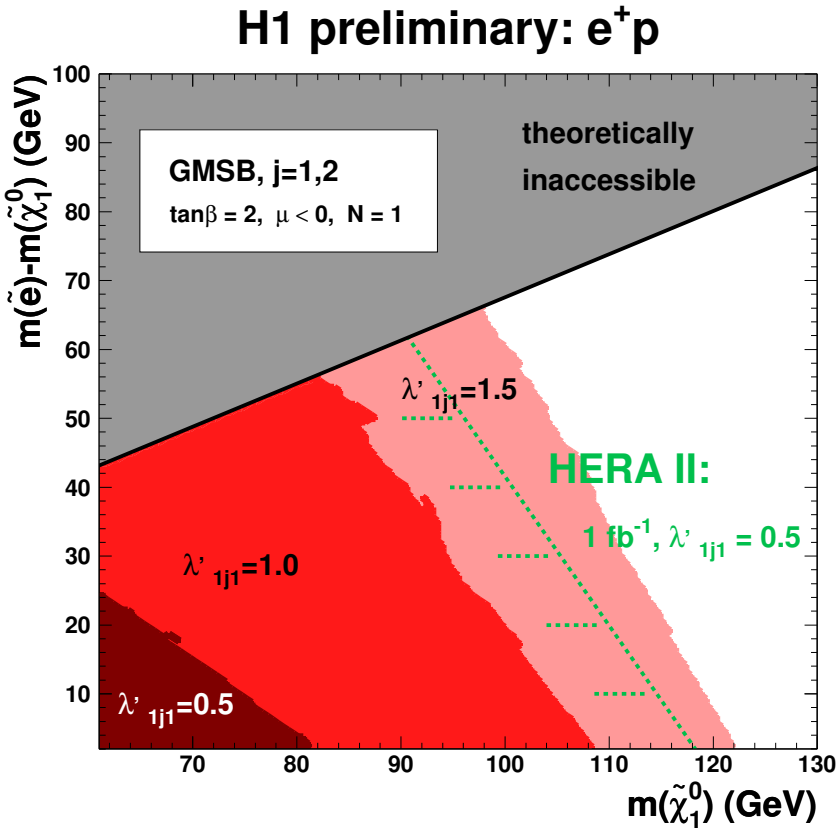




Summary and Outlook

- **Squarks in RPV SUSY has been searched in many decay channels**
  - Using data >64 pb^{-1} e^+p and >13 pb^{-1} e^-p at $\sqrt{s}$ = ~320 GeV
  - No deviation from SM found
    - ⇒ Significant constraints on MSSM and mSUGRA parameters
    - ⇒ Squark masses up to ~280 GeV excluded for $\lambda'_{1jk} = 0.3$ ($\sim \sqrt{4\pi\alpha_{em}}$)
    - ⇒ Stop masses up to ~275 GeV excluded for $\lambda'_{131} = 0.3$

- **Superlight Gravitinos in GMSB:**
  - First time at HERA: Limits on λ'_{ijk} independent of squark masses



- **Prospects for HERA2:**
  - Polarised beams probe directly:

$$e_R^+ + d_L \rightarrow \tilde{u}_L, \tilde{c}_L, \tilde{t}_L$$
$$e_L^- + u_L \rightarrow \tilde{d}_R, \tilde{s}_R, \tilde{b}_R$$

  - Gravitinos:
    - H1 and ZEUS luminostiy:
      0.5 + 0.5 fb^{-1}, $\lambda'_{1j1} = 0.5$